A PC-Based Tool for Coupled CFD and CSD Simulation of Blast-Barrier Responses

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ABSTRACT

An integrated experimental, analytical, and computational effort is being made in the Center for Explosion Resistant Design, in collaboration with national laboratories and industry, on the structural design, first-principle simulation, and development of an empirical model and PC-based code for predicting the responses of a blast barrier. To catch the essential feature with an effective simulation tool, an axisymmetrical model is formulated to predict the blast environment in the presence of a barrier with the use of a coupled computational fluid dynamics (CFD) and computational solid dynamics (CSD) simulation procedure based on previous work. This coupled CFD and CSD simulation procedure is designed via the Material Point Method (MPM) in spatial discretization that is an extension from CFD to CSD. The scaled blast experimental databases from small-scale tests performed by the national laboratories are employed to determine the gaps in the database that indicate a need for additional experiments. An empirical model is developed based on the experimental data and the first-principle simulation model. System identification models are then established to predict the blast pressure based on a range of parameters such as bomb size and position, wall dimensions, angle of incident, and location of target. In collaboration with the Air Force Research Laboratory (AFRL), the proposed model-based simulation procedures are verified and improved with full-scale experiments, and the structural design of the barrier prototype is examined for near-field blast loads to evaluate various confinement strategies and materials. Based on the above results, the empirical model will be implemented into a user-friendly PC-based code for predicting the blast pressure and impulse on structures in the presence of the prototype blast barrier. In the presentation, recent research results on the coupled CFD and CSD simulation of blast-barrier responses will be discussed.

SIMULATION PROCEDURE

To develop an effective computer test-bed for the first-principle simulation of blast-resistant design, a coupled computational fluid dynamics (CFD) and computational solid dynamics (CSD) procedure has been proposed with the use of the Material Point Method (MPM) [Chen, 2002; Chen et al., 2002; Hu and Chen, 2005; among others]. As one of the innovative spatial discretization methods, the MPM is an extension to solid mechanics problems of a hydrodynamics code called FLIP which, in turn, evolved from the Particle-in-Cell Method. The motivation of the development was to simulate problems such as impact/contact, penetration, and perforation with history-dependent internal state variables as shown in the early publications about the MPM [Sulsky et al., 1994 and 1995]. The essential idea is to take advantage of both the Eulerian and Lagrangian methods while avoiding the shortcomings of each. In comparison with the other meshless methods, the MPM appears to be less complex, with a cost factor of at most twice that associated with the use of corresponding finite elements, and easily interfaced with existing finite element codes as reviewed by Chen et al. [2002]. In addition, the use of the single-valued mapping functions in the MPM results in a natural no-slip contact/impact scheme so that no inter-penetration would occur. The applications of the MPM to other dynamic problems have further demonstrated the potential of the MPM for model-based simulation of multi-physical phenomena [Chen et al., 2005; Hu and Chen, 2003; Shen and Chen, 2005; among others]. Based on the MPM, a computer test-bed is being developed to integrate three basic types of governing differential equations (hyperbolic, parabolic and elliptic ones) into a single computational domain to perform first-principle simulation of blast-resistant design. The essential idea of the spatial discretization procedure for different kinds of gradient and divergence operators is outlined as below.

The spatial discretization procedure describes a continuum body with the use of a finite set of N_p material points in the original configuration that are tracked throughout the deformation process. Let $\boldsymbol{x}_p^t$ ($p = 1,2,...,N_p$) denote the current position of material point *p* at time *t*. Each material point at time *t* has an associated mass M_p, density ρ_p^t, velocity $\boldsymbol{v}_p^t$, Cauchy stress tensor $\boldsymbol{s}_p^t$, strain $\boldsymbol{e}_p^t$, and any other internal state variables necessary for a constitutive model. Thus, these material points provide a Lagrangian description of the continuum body. Since each material point contains a fixed amount of mass for all time, the conservation of mass is automatically satisfied. At each time step, the information from the material points is mapped to a background computational mesh (grid). This mesh covers the computational domain of interest, and is chosen for computational convenience. After the information is mapped from the material points to the mesh nodes, the discrete equations of the conservation of momentum can be solved on the mesh nodes. The weak form of the conservation of momentum can be found, based on the standard procedure used in the FEM, to be

$$\int_\Omega \rho \boldsymbol{w} \cdot \boldsymbol{a} d\Omega = -\int_\Omega \rho \boldsymbol{s}^{\boldsymbol{s}} : \nabla \boldsymbol{w} d\Omega + \int_{S^c} \rho \boldsymbol{c}^{s} \cdot \boldsymbol{w} dS + \int_\Omega \rho \boldsymbol{w} \cdot \boldsymbol{b} d\Omega \qquad (1)$$

in which *w* denotes the test function, *a* is the acceleration, $\boldsymbol{s}^{\boldsymbol{s}}$ is the specific stress (i.e., stress divided by mass density), $\boldsymbol{c}^{\boldsymbol{s}}$ is the specific traction vector (i.e., traction divided by

mass density), b is the specific body force, Ω is the current configuration of the continuum, and S^c is that part of the boundary with a prescribed traction. The test function w is assumed to be zero on the boundary with a prescribed displacement. Since the whole continuum body is described with the use of a finite set of material points (mass elements), the mass density term can be written as

$$\rho(\boldsymbol{x},t) = \sum_{p=1}^{N_p} M_p \delta\left(\boldsymbol{x} - \boldsymbol{x}_p^t\right) \tag{2}$$

where δ is the Dirac delta function with dimension of the inverse of volume. The substitution of (2) into (1) converts the integrals to the sums of quantities evaluated at the material points; namely,

$$\begin{aligned} &\sum_{p=1}^{N_p} M_p \left[\boldsymbol{w}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right)\cdot \boldsymbol{a}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right)\right] \\ &= \sum_{p=1}^{N_p} M_p \left[-\boldsymbol{s}^{\boldsymbol{s}}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right) : \nabla \boldsymbol{w}\big|_{\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}}} + \boldsymbol{w}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right)\cdot \boldsymbol{c}^{\boldsymbol{s}}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right) h^{-1} + \boldsymbol{w}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right)\cdot \boldsymbol{b}\left(\boldsymbol{x}_{\boldsymbol{p}}^{\boldsymbol{t}},t\right)\right] \end{aligned} \tag{3}$$

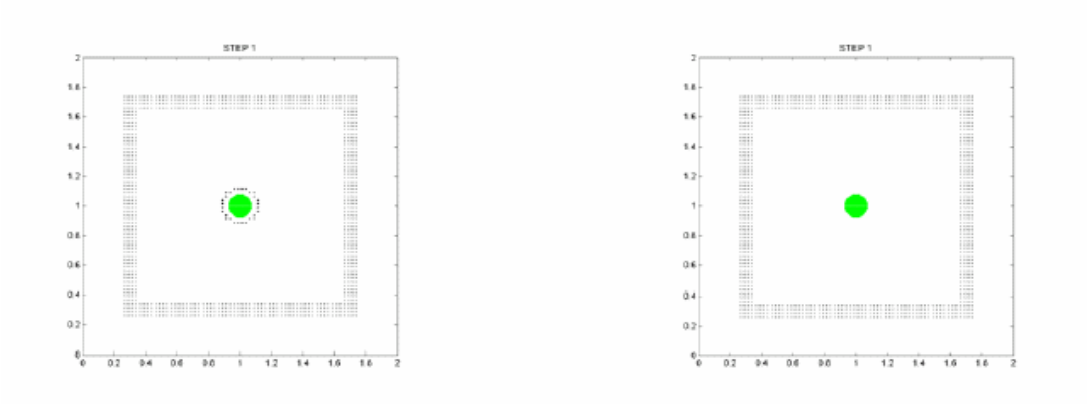
with h being the thickness of the boundary layer. As can be seen from (3), the interactions among different material points are reflected only through the gradient terms, and a suitable set of material points must be chosen to represent the boundary layer.

DEMONSTRATION OF PC-BASED COMPUTER CODE

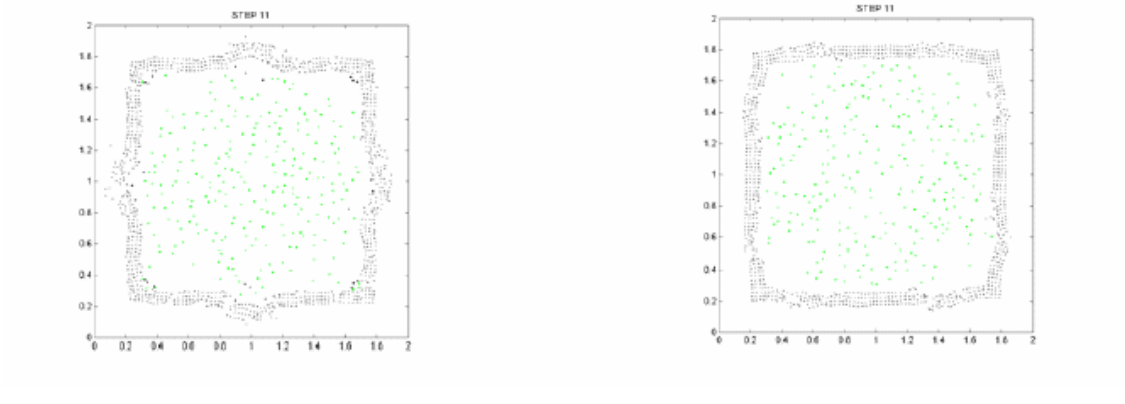
To demonstrate the potential of the simulation procedure, a bomb with and without casing is placed in the center of a square concrete tube, respectively. The concrete, air, steel case, and bomb are represented by different kinds of material points based on the respective constitutive behaviors. As shown in the following snapshots, the coupled CFD and CSD responses could be investigated to better understand the blast-resistant design.

In the presentation, the coupled CFD and CSD responses of blast-barriers will be simulated and verified with the experimental data. The important issues such as artificial viscosity, stability, and convergence of numerical solutions will be explored. The comparison between the numerical solutions obtained by the proposed simulation procedure and LS-DYNA will also be made, and future work will be discussed based on the current research results.

The first-principle-based simulation procedure verified with existing field tests will be used to create the pressure environment in the presence of a blast barrier with a variety of design parameters. The parameters will include the size of the bomb, the distance from the bomb to the barrier and from the barrier to the target, the height of the barrier, the angle of incident, and the location of the bomb above ground level. The computer simulation will be performed to populate the database which will be used in a neural network model to predict the pressure and impulse based on the input parameters. The prediction model generated by the neural network analysis is then employed in a user-friendly PC-based computer code, which will allow blast designers and engineers to quickly determine the loads on a structure during a blast event in the presence of a blast barrier.



EXPLOSIVE PROFILES AT TIME I WITH AND WITHOUT CASING



EXPLOSIVE PROFILES AT TIME II WITH AND WITHOUT CASING

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14. ABSTRACT

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